QUICK LAB

Quantum Pennies

TARGET SKILLS

- Hypothesizing
- Analyzing and interpreting

This Quick Lab will give you some insight into the approach that Robert Andrews Millikan (1868–1953) used to determine the charge on the electron. Instead of charge, however, you will determine the mass of a penny.

Your teacher has prepared a class set of small black film canisters that contain various numbers of identical pennies. You and your classmates will use an electronic balance to determine the mass of each film canister and its contents. Carry out this procedure and post the class results.

Analyze and Conclude

1. Draw a bar graph, with the canister number on the horizontal axis and the mass of that canister on the vertical axis.
2. Calculate and record the increments between each mass value and all other mass values.
3. Is there any minimum increment of which all other increments are a multiple?
4. What do you predict to be the mass of a penny? Check your prediction by direct measurement.

Apply and Extend

5. As a class, open the canisters and randomly add or remove pennies. Again, measure the mass, and repeat the analysis.

Millikan's Oil-Drop Experiment: Charge on the Electron

A very important series of experiments dependent on the uniform electric field between a pair of parallel plates was performed during the years 1909 to 1913 by Millikan. The results of these experiments, together with his contributions to research on the photoelectric effect (see Chapter 12), led to his Nobel Prize in Physics in 1923. Millikan was able not only to verify the existence of a fundamental electric charge — the electron — but also to provide the precise value of the charge carried by the electron. This had a tremendous impact on the further development of the theory of the structure of matter.

The experimental procedures used by Millikan were actually a modification of earlier techniques used by J.J. Thomson (1856–1940). A pair of parallel plates was very finely ground to smoothness and a tiny hole was drilled in the top plate. An atomizer was mounted above the plates and used to spray tiny droplets of oil into the region above the plates. These oil droplets acquired an electric charge as they were sprayed, presumably from friction. The whole apparatus was kept in a constant-temperature enclosure, and the region between the plates was illuminated with an arc lamp.

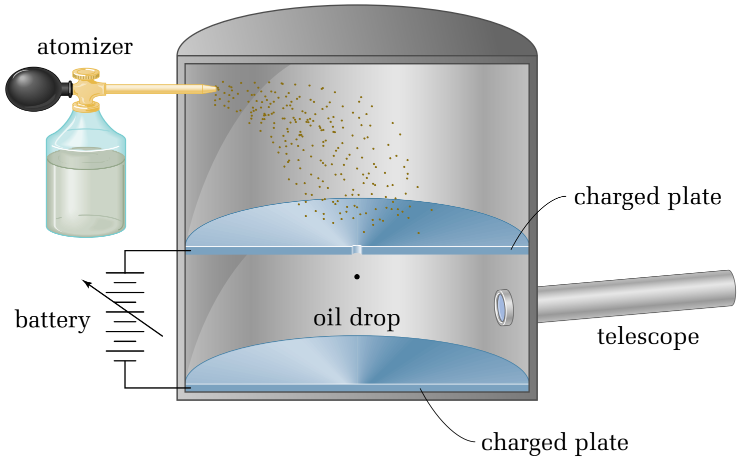

Figure 8.6 Not shown in this simplified cross-section of Millikan's apparatus is a source of X rays that could ionize the air in the electric field.

A droplet that fell through the hole and into the region between the plates could be viewed through a short telescope. The droplet would very quickly acquire terminal velocity as it fell under the influence of the force of gravity and the resistance (viscosity) of the air. This terminal velocity, v_0, could be measured by timing the drop as it fell between the lines on a graduated eyepiece. (In Millikan's apparatus, the distance between the cross hairs was 0.010 cm). A potential difference (3000 to 8000 V) was then applied across the plates (separated 1.600 cm) by means of a variable battery.

Usually the oil drops had attained a negative charge, so the potential difference would be applied so that the top plate was made positive. In that way, a negatively charged oil drop could be made to reach an upward terminal velocity under the action of the applied electric field, its effective weight, and air friction. This second terminal velocity, v_1, was also recorded.

Millikan then directed X rays to the region between the plates. The X rays ionized the air molecules between the plates and caused the charge on the oil drop to change as it either gained or lost electrons. Again, the procedure of determining the two terminal velocities, one with and one without the applied electric field, could be repeated many times with differently charged oil drops.

Millikan observed that the terminal velocity of the charged oil drops, which depended on the charge itself, varied from trial to trial. Over a very large number of trials, however, the velocity values could be grouped into categories, all of which represented an integral multiple of the lowest observed value. This led him to conclude that the charge on the oil drops themselves could be quantified as integral multiples of one fundamental value. Millikan then applied a mathematical analysis to determine that value. The following is a simplified version of Millikan's analysis.

- When the oil drop travelled with a uniform velocity, the upward electric force was equal in magnitude to the downward gravitational force.

$$\vec{F}_Q = \vec{F}_g$$

- Write the expressions for the electric force in terms of the electric field intensity and for the gravitational force.

$$\vec{E}_Q = \frac{\vec{F}_Q}{q} \qquad \vec{F}_g = m\vec{g}$$

$$\vec{F}_Q = q\vec{E}_Q$$

- Substitute the expressions into the first equation.

$$q\vec{E}_Q = m\vec{g}$$

- Express the electric field intensity in terms of the potential difference across the plates.

$$E_Q = \frac{\Delta V}{\Delta d}$$

- Substitute the expression for the electric field intensity.

$$\frac{qV}{\Delta d} = mg$$

- Solve for the charge, q.

$$q = \frac{mg\Delta d}{V}$$

All of the variables in this equation for q could be measured easily, except the mass. Millikan then turned to the work of Sir George Gabriel Stokes (1819–1903), a British mathematician and physicist who had helped to develop the laws of hydrostatics. Based on a particle's rate of fall as it falls through a viscous medium, **Stokes' law** can be used to calculate the particle's mass.

Millikan measured the terminal velocity of each oil drop with the battery turned off, that is, the rate of fall under the influence of gravity and the resistance of the fluid (air) only. When he substituted the mass of each oil drop into the equation for the charge q, above, he found that the magnitude of the charge on each oil drop was always an integral multiple of a fundamental value. He assumed that this particular fundamental charge was actually the charge on the electron, and the multiple values arose from the oil drops having two, three, or more excess or deficit electrons.

The electronic charge computed from many trials of Millikan's method is found to be $e = 1.6065 \times 10^{-19}$ C, which agrees well with values determined by other methods. The currently accepted value for the charge on the electron is $e = 1.602 \times 10^{-19}$ C. Knowing the charge, e, on an electron, it has become common practice to express the charge on an object in terms of the number, n, of the excess or deficit of electrons on the object, or $q = ne$.

SAMPLE PROBLEM

Millikan Experiment

Two horizontal plates in a Millikan-like apparatus are placed 16.0 mm apart. An oil drop of mass 3.00×10^{-15} kg remains at rest between the plates when a potential difference of 420.0 V is applied across the plates, the upper plate being positive. Calculate the

(a) net charge on the oil drop

(b) sign of the charge on the oil drop

(c) number of excess or deficit electrons on the oil drop

Conceptualize the Problem

- The oil drop is held in place by its own *weight* (down) and the *electric force* (up).
- The *electric force* depends on the *electric field* value between the plates.

Identify the Goal

The magnitude of the charge, q, on the oil drop; its sign, ±; and electron number, n, of excess or deficit electrons

Identify the Variables and Constants

Known	Implied	Unknown
$d = 16.0$ mm	$g = 9.81\ \frac{\text{m}}{\text{s}^2}$	q
$m = 3.00 \times 10^{-15}$ kg	$e = 1.602 \times 10^{-19}$ C	n
$V = 420.0$ V		

Develop a Strategy

The electric force will be equal in magnitude to the force of gravity.

$$F_Q = F_g$$

$$qE_Q = mg$$

$$q\frac{V}{\Delta d} = mg$$

$$q = \frac{mg\Delta d}{V}$$

$$q = \frac{(3.00 \times 10^{-15}\ \text{kg})\left(9.81\ \frac{\text{m}}{\text{s}^2}\right)(1.60 \times 10^{-2}\ \text{m})}{420.0\ \text{V}}$$

$$q = 1.1211 \times 10^{-18}\ \text{C}$$

$$q \cong 1.12 \times 10^{-18}\ \text{C}$$

(a) The charge on the oil drop is -1.12×10^{-18} C.

The drop was suspended.

Since the electric force was in a direction opposite to the gravitational force, it had to be "up." The upper plate was positive, so the charge had to be negative.

(b) The net charge was negative.

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The net charge is related to the charge on the electron.

$$n = \frac{q}{e}$$

$$n = \frac{1.12 \times 10^{-18}\,\text{C}}{1.60 \times 10^{-19}\,\text{C}}$$

$$n = 7.00$$

(c) There is an excess of seven electrons on the oil drop, causing its net negative charge.

Validate the Solution

The values are consistent with the size of the oil drop, the plate separation, and the potential difference. The units in the calculation are consistent.

$$\frac{\cancel{\text{kg}} \cdot \frac{\text{N}}{\cancel{\text{kg}}} \cdot \text{m}}{\text{V}} = \frac{\text{N} \cdot \text{m}}{\frac{\text{J}}{\text{C}}} = \frac{\cancel{\text{J}}}{\frac{\cancel{\text{J}}}{\text{C}}} = \text{C}$$

PRACTICE PROBLEMS

9. Two large horizontal parallel plates are separated by 2.00 cm. An oil drop, mass 4.02×10^{-15} kg, is held balanced between the plates when a potential difference of 820.0 V is applied across the plates, with the upper plate being negative.

(a) What is the charge on the drop?

(b) What is the number of excess or deficit electrons on the oil drop?

10. A small latex sphere experiences an electric force of 3.6×10^{-14} N when suspended halfway between a pair of large metal plates, which are separated by 48.0 mm. There is just enough electric force to balance the force of gravity on the sphere.

(a) What is the mass of the sphere?

(b) What is the potential difference between the plates, given that the charge on the sphere is 4.8×10^{-19} C?

11. The density of the oil used to form droplets in the Millikan experiment is $9.20 \times 10^{2}\ \text{kg/m}^{3}$ and the radius of a typical oil droplet is 2.00 μm. When the horizontal plates are placed 18.0 mm apart, an oil drop, later determined to have an excess of three electrons, is held in equilibrium. What potential difference must have been applied across the plates?

UNIT PROJECT PREP

Understanding the costs and benefits of any issue often begins by (a) gathering useful facts and (b) identifying personal bias.

- Identify your bias. Do you believe that fundamental research is worthwhile if it does not have any obvious applications?
- Do you believe that research resulting in greater understanding will some day, perhaps decades later, be put to use in an application?
- How would you complete the statement "Knowledge for the sake of knowledge … "?